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A STABLE VOLTAGE-CONTROLLED VARIABLE FREQUENCY OSCILLATOR

16 AUGUST 1962

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 62-105

$1.60

A STABLE VOLTAGE-CONTROLLED VARIABLE FREQUENCY OSCILLATOR

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ABSTRACT: A transistorized oscillator was required with a frequency stability of 1 part in 2 x 10^5 per hour. The frequency was 20.460 kc, variable ± 15 cps by a dc control voltage. The design philosophy and techniques are presented, including a high Q tuned circuit, frequency variation control, feedback stabilization, temperature compensation, and thermal filtering. Test results show that all requirements were met or exceeded. Methods of measuring the frequency to this accuracy are discussed.

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PUBLISHED OCTOBER 1962

U. S. NAVAL ORDNANCE LABORATORY
White Oak, Maryland

This report describes the development, theory and operation of an extremely stable transistorized oscillator. The project was funded under Task Number NOL 396. This report will be of interest to anyone requiring a compact, highly stable, low power, variable frequency oscillator.

R. E. ODENING

Zaka I Slawsky

Z. I. SLAWSKY
By direction

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INTRODUCTION

1. The oscillator to be described has a frequency stability approaching that of low frequency crystal oscillators, and yet it is possible to change its frequency of oscillation over a substantial range by an input voltage control. A crystal oscillator can be varied only over a very narrow frequency range. The oscillator was developed to meet a requirement for a highly stable adjustable timing source in an automatic control loop system but the results are considered of sufficient interest to justify a report on the oscillator alone. The design philosophy and techniques will be presented along with the results achieved.

2. Design Specifications.

A. Frequency.

The desired center frequency of this oscillator was to be 20.460 kc per second.

B. Frequency Control.

It was necessary to control the frequency by a variable dc voltage ranging between zero and -3 volts. The amount of control was desired to be $\pm$ 100 cps. If it proved too difficult to meet the stability requirement of the next paragraph and still have this much frequency range available, it was recognized that it would be satisfactory if the voltage control would produce a $\pm$ 15 cps frequency change with the rest of the necessary change being covered by mechanical rotation of an air trimmer condenser.

C. Short Term Stability.

It was required that, for a constant value of control voltage, the frequency of this oscillator not change by more than 1/10 cps per hour. It was also important that this change take place slowly and at a relatively uniform rate over the period of an hour. In other words it was desired that there be no particular transient changes in frequency. Thus the stability requirement may be stated as a rate of change not exceeding one part in 2×10^5 per/hr.

D. Long Term Stability.

The requirements here were not particularly stringent. It was merely desired that the long term stability as measured over a period of months should not exceed $\pm$ 10 cps.

E. Type of Electronics.

It was necessary that the oscillator be completely transistorized in order to meet low battery drain requirements.

F. Power Supply.

In order to be compatible with the rest of the system it was required that the power supply be a single 6 volt negative supply. If necessary to achieve adequate frequency stability it was acceptable that a dry battery supply be used. The power drain, however, had to be sufficiently small so that a single set of batteries could power the oscillator satisfactorily for at least a week's continuous operation.

G. Temperature Range.

It was required that the oscillator operate satisfactorily over an ambient room temperature range of 50° to 90°F.

H. Interaction With Other Oscillators.

It was extremely important that there be no detectable tendency for this oscillator to lock in with a similar oscillator operating at approximately the same frequency and located as close as 3 feet away.

OSCILLATOR DESIGN

3. A block diagram of the oscillator is shown in Figure 1. A detailed circuit diagram is shown in Figure 2. The basic system used was an LC tuned circuit with a secondary winding to provide the feedback. An LC circuit was chosen over the competing RC types because it was capable of higher values of Q for greater frequency stability, as well as permitting single element capacitance variation for frequency control. Means of converting a variable control voltage to a variable capacitance seemed more stable and satisfactory than systems for varying resistance or inductance. Each major block will be discussed below as a separate unit.

A. The Tuned Circuit.

4. For frequency stability of a high order it is necessary to use a coil with a very high Q. The rate of change of phase shift versus frequency at resonance is approximately proportional to the Q of the tuned circuit. Any variation in the phase shift of the amplifier must result in a sufficient change in frequency to produce a compensating equal and opposite phase shift in the tuned circuit. This means that the more rapidly the phase shift changes with frequency in the tuned circuit the smaller will be the changes in frequency of the oscillator due to amplifier changes.

5. For the coil core, a Western Electric No. 472411 molybdenum permalloy dust core was chosen. It has a μ of 26. The primary was wound with 500 turns of # 40/38 Litz wire. A secondary was wound with 177 turns of # 30 solid copper wire. The final coil had a Q of approximately 300 at 20 kc. The use of Litz rather than the equivalent solid wire for the primary almost doubled the Q of the coil. Since there were practically no current losses in the secondary winding, small copper wire appeared to be quite adequate.

6. It was found necessary to use silver mica condensers for the tuned circuit. This was done partly because they tend to be more stable than other types but primarily because the use of paper or plastic dielectric condensers reduced the Q of the tuned circuit by a factor of 2 or 3 over that obtained with silver mica condensers. The inductance of the coil was approximately 10 millihenrys and the necessary tuning capacitance on the order of 6400 $\mu\mu$f. The coil was mounted inside a small copper shield can to reduce the effect of interaction with other coils in nearby locations.

7. In order to retain the advantage of the high Q of the tuned circuit it is necessary to drive it from a high impedance source. A ten millihenry inductance at 20 kc has an impedance of about 1300 ohms. With a Q of 300 this means that the tuned circuit presents an impedance of about 390,000 ohms. Using a series dropping resistor of 3.9 megohms means that there is a voltage loss in the tuned circuit of about 10 to 1, but that the Q is decreased by a rather negligible quantity.

B. Frequency Control System.

8. The controlled frequency feature was obtained through the use of a varicap in parallel with the capacitance of the tuned circuit. A varicap is a negatively biased silicon diode designed so that the effective capacitance is a function of the

amount of dc bias across it. The effective capacitance decreases with increasing negative bias. Fig. 3 shows a curve of the frequency of the oscillator as a function of control bias for the particular circuit elements shown in Fig. 2. The control voltage is fed through an 8.2 megohm resistor, so that the Q of the circuit will not be lowered.

9. If the control voltage region between -0.5 and -2.5 volts is selected, a range of frequency variation of 30 cps is obtained, the ± 15 cps stipulated in the requirements. The variation of frequency is not a linear function of control voltage. While this is unfortunate, there does not appear to be any satisfactory voltage controlled variable capacitance which will be substantially more linear. An attempt was made to reduce the nonlinearity by using a small coupling capacitor of 180 μμf to couple the varicap into the tuned circuit. At low bias voltages the effective capacitance seen by the tuned circuit approaches a limiting value set by the coupling capacitor. This is the region where the capacitance of the varicap increases rapidly. Therefore a certain straightening effect takes place at the low voltage end of the frequency vs. control voltage curve.

10. If it had been desired to increase the range of frequency control, this could have been accomplished in two ways. First, the coupling condenser could have been increased in size. Second, an additional one or more varicaps could have been connected in parallel with the existing one, or a different type with a larger effective capacitance could have been used. Since the varicap was one of the sources of frequency instability, it was decided to use the minimum possible control range of ± 15 cps and to adjust an air trimmer condenser when it was desired to change the center of the operating frequency range.

C. Feedback Stabilized Amplifier.

11. It was shown in Section A that any changes in phase shift in the amplifier section of the oscillator must be compensated for by changes in the phase shift, and hence the frequency, in the tuned circuit. It follows then that to build an oscillator of high frequency stability, it is necessary that the amplifier should have not only a stable gain, but also a phase shift which does not change with frequency and is as close to zero as possible in the region of oscillation. One of the easiest ways to accomplish this goal is to use an amplifier whose gain is stabilized by negative feedback, and whose low natural phase shift is held at essentially zero by the use of a generous amount of non-frequency sensitive negative feedback.

12. The computation of the gain necessary in this amplifier is relatively simple. The use of the large series resistor with the tuned circuit means that there is a voltage loss of approximately 10 to 1 in the tuned circuit. A further loss of approximately 3 to 1 in voltage occurs in the step down ratio between the primary and secondary of the coil. Thus, it is necessary to supply a voltage gain of approximately 30 in the feedback stabilized amplifier. Approximately 20 db of negative feedback is required in the amplifier to achieve really significant improvement. Therefore, it is necessary to design the amplifier with a voltage gain of approximately 300 before feedback is applied. Transistors T4 through T7 in Fig. 2 constitute the feedback stabilized amplifier. The design of this amplifier section is considered sufficiently conventional so that no further discussion of it will be presented here.

D. High Impedance Input Circuit.

13. The input impedance of the amplifier section is very low. Therefore it is necessary to design an impedance matching circuit which will present a high impedance to the secondary winding of the coil. A single emitter-follower stage gives a substantial ratio of impedance transformation, as well as power gain. However, to achieve the very high input impedance which was needed here, a single emitter-follower was not adequate. First it is necessary to decide just how high an input impedance is needed. The actual impedance of the secondary winding of the coil is on the order of only 50,000 ohms. Therefore, an input impedance of the order of a half megohm would not substantially load down the secondary in the sense that it would decrease the amplitude of voltage. However, substantial changes in the input impedance will occur with temperature, power supply changes, etc. With the input impedance at the order of a half megohm, these variations could change the Q enough to produce appreciable changes of phase angle in the tuned circuit. Therefore, it was decided to provide an input impedance of at least 5 megohms if possible. This was done thru the successive transistor stages T_3, T_2 and T_1 in Fig. 2. The emitter-follower stage T_3 is capable of driving a low impedance load such as the input of the amplifier section. It presents an input impedance by itself on the order of 20 thousand ohms. The preceding emitter-follower stage T_2 then is loaded with a relatively high impedance and it in turn presents a input impedance on the order of a couple hundred thousand ohms. The addition of the negative feedback loop from the output of T_3 to the input of T_2 raises the input impedance of the combination to approximately 1 megohm. The final transistor T_1 was chosen to be an emitter-follower stage

utilizing a silicon transistor. A silicon transistor has the advantage of a much lower I_{co} then does a comparable germanium type. This permits the use of a much higher load resistance. It also draws much less dc bias current through the secondary winding of the coil. The final advantage of the silicon transistor is that the percentage change of I_{co} with temperature is much less than that for a corresponding germanium type. Thus, it presents considerable advantages in terms of stability for the input stage of this section. The measured input impedance for the entire circuit was determined to be greater than 5 megohms for a -6 volt supply. It would be possible to secure higher input impedances by the use of a higher supply voltage.

E. Temperature Compensation.

14. Fairly early in the design of this oscillator it became apparent that temperature was the greatest contributor to frequency instability. Transistors are notoriously temperature sensitive. Before the addition of the negative feedback stabilization feature to the amplifier, if a person used his fingers to heat any one of the transistors in the amplifier, there would be a noticable drift in frequency. The addition of negative feedback stabilization reduced this effect to the point where it was essentially undetectable. Similarly before the use of a multiple stage input impedance circuit the transistors in the input impedance transforming circuit were extremely temperature sensitive. Again the final circuit is essentially unaffected by the temperature of the transistors.

15. Unfortunately the same thing cannot be said of the tuned circuit components. Essentially there are 3 separate units involved in the tuned circuit stability problem. First, the inductance (principally the core), second, the main or fixed capacitance, and third, the varicap capacitance. Ideally it would be desirable to reduce the temperature coefficient of all three units individually to zero. As a practical matter the best that can be done is to compensate one with the other. Frequency measurements were made with the various components held at 21° and 24°C, as this was felt to be in the most probable room temperature range. The most satisfactory core that we could obtain had a negative temperature coefficient of approximately -50 parts per million per degree Centrigrade. Silver mica condensers, such as were needed from the standpoint of a high Q, have a positive temperature coefficient of approximately +30 ppm/°C. This leaves a net negative temperature coefficient of approximately -20 ppm/°C for the fixed portion of the tuned circuit.

16. Fortunately the varicap has a large positive temperature

coefficient. Measurements at one particular control voltage and temperature showed a positive coefficient of +2200 ppm/°C. This large coefficient required that the magnitude of the capacitance generated by the varicap be kept on the order of 1/100 of the fixed capacitance. Otherwise the temperature variation in capacitance of the varicap could easily swamp out the smaller equivalent negative temperature coefficient of the fixed tuned circuit. Using this criterion, the final design has a reasonably well temperature compensated total tuned circuit. It should be remembered, however, that as the effective capacitance of the varicap changes with control voltage, the net overall temperature coefficient also changes. Hence it is impractical to achieve perfect temperature compensation by this appraoch.

17. Therefore, the next step was to reduce the rate of temperature change which the tuned circuit would see. This was done by utilizing a large heat sink placed in an insulated box with the entire electronic circuitry placed inside the heat sink. A two chamber box was constructed of one-inch thick aluminum with all components of the tuned circuit going in the smaller chamber and the balance of the electronics and the batteries going in the larger chamber. This 47 pound aluminum heat sink was then placed inside a wooden box with foam polystyrene insulation between the wood and the aluminum. The heat sink acts as a thermal capacitance, while the wooden box and foam insulation act as a thermal resistance. The two elements in series form an equivalent circuit fed from a constant current heat source proportional to the temperature difference between the inside of the chambers and room temperature.

18. This arrangement very effectively eliminated any rapid changes in temperature of the tuned circuit and hence any rapid fluctuations in the frequency of the oscillator due to temperature effects. Table I gives data for the overall frequency fluctuations as measured throughout a 33 hour period wihh normal substantial changes taking place in the ambient temperature of the room. The room temperature was not recorded, but it varied over a range of more than 10°F. The column headed "aluminum box temperature" was measured with a glass bulb type thermometer inserted through a hole in the wood and foam insulation into a 3/4 inch deep hole drilled in the aluminum and filled with oil. The bulb itself was therefore in the aluminum of the box, but some heat was undoubtedly transferred along the glass body of the thermometer. It was also difficult to read the thermometer to 0.1°C. The final column in Table I shows a computed rate of change of frequency as a function of time which is a measure of the important criterion of short

Table I Frequency Stability Test Results

Time May 9, '62	Alum. Box Temp.	Freq. rel. to Crystal Osc.	Δf/Δt cps/hr
0735 hrs.	24.6°C	.000 cps	——
0800	24.6	+.018	+.043
0915	24.6	+.063	+.036
1015	24.8	+.046	-.017
1045	24.9	+.021	-.050
1100	24.9	.000	-.084
1115	25.0	-.024	-.096
1145	25.0	-.057	-.066
1230	24.9	-.104	-.063
1300	25.1	-.130	-.052
1330	25.0	-.153	-.046
1400	25.0	-.170	-.034
1430	25.0	-.190	-.040
1500	25.0	-.206	-.032
1530	25.0	-.217	-.022
1600	25.0	-.234	-.034
1750	25.1	-.333	-.054
3400	25.8	-.830	-.031
3700	26.0	-.945	-.038
3820	26.0	-1.000	-.041
4020	26.1	-1.110	-.055
4100	26.1	-1.140	-.045

term stability. At no time during the run did this rate exceed the goal of not more than 0.1 cps/hour. These results are extremely good for a variable frequency oscillator which does not have a temperature controlled oven.

F. Output Isolation Amplifier.

19. Transistors T8 and T9 with their associated circuitry constitute the isolation amplifier and clipper which we used for our particular purposes. The result was to furnish not only isolation between the load and the tuned circuit but also to generate a square wave form. If the square wave feature were not desired, a simple two stage emitter-follower section would have been quite adequate.

G. Power Supply.

20. The circuit was designed to work from a 6 volt negative supply. The current drain at normal voltage is 9 ma. The total power consumption of the oscillator together with its isolating amplifier is thus only 54 milliwatts. With this small power drain, battery operation for the power supply is completely practical. For example one pound of mercury cell batteries would be capable of operating this oscillator for over a month's continuous operation 24 hours a day. A big advantage in the use of batteries for the power supply is the fact that it eliminates any possibility of electrical coupling of this oscillator to any other through a common power supply.

21. Tests were run to determine the variation in oscillator frequency as the power supply voltage changed. The results are presented in Fig. 4. Varying the power supply voltage from -2 volts to -10 volts changed the frequency of oscillation by less than 1 cycle in 20,000. Being able to vary the supply voltage over a 5 to 1 range with so little change in frequency demonstrates the effectiveness of the negative feedback stabilization in the amplifier and the input circuit.

FREQUENCY MEASUREMENT PROCEDURES

22. The frequency stability of this oscillator was great enough so that measuring the fluctuations accurately presented something of a problem. A standard commercial counter based on a self contained high frequency crystal oscillator was quite adequate to give gross values of the oscillator frequency, and such a counter was used. For example, Fig. 3 showing the curve of frequency vs. input control voltage was taken with a counter. Such counters however have a limit to their accuracy of $\pm$ 1 count. Usually this is equivalent to $\pm$1 cps.

23. For stability runs such as are shown in Table I, we needed a precision of 0.001 cps as a minimum. We attained this by using a cathode ray oscilloscope as a phase comparator between the oscillator under test and a low frequency crystal controlled standard. A Tektronix CRO with a dual trace preamp was synchronized with the crystal oscillator operating at 20,460 cps. The sweep speed was adjusted to present just over 50μs, or 1 full cycle, of both oscillator signals for full scale horizontal deflection. The trace for the crystal oscillator would stay fixed, while the variable oscillator trace would drift slowly past it. If for example it drifted to the left one full cycle in 50.0 seconds, the frequency was 0.020 cps higher than the crystal oscillator. By using a stopwatch to time corresponding points on the square wave output for several cycles of drift, it was quite easy to achieve a precision of 0.001 cps. Also if the rate of drift remained constant over a period of a few minutes, we knew that there was no rapid fluctuation in frequency. This also served as an effective way to check for interaction between oscillators. Interaction shows up as a tendency to lock in, or for the rate of drift to change cyclically. In extremely severe cases, the two oscillators will even lock together for several seconds and then snap past to the next cycle.

24. The question soon arose, however, as to whether or not the crystal oscillator was sufficiently stable for our purposes. The method of checking this was to compare two different but similar crystal oscillators. The initial results were that the two varied enough so that the difference was on the order of 0.01 cps/hr. This of course meant that they were not adequate. Again, the solution was to place the crystals in insulated heat sinks, as they were not oven temperature controlled. When this was done, the two crystals achieved a stability approaching 0.001 cps/hr relative to each other, which we deemed adequate.

CONCLUSIONS

25. A study of the above results shows that the design of this oscillator was highly successful. The oscillator in the final design operates at 20.460 kc with a range of variation of ± 15 cps controllable by a variable dc voltage. The short term frequency stability is one part in 2 x 10^5 per/hour. The unit is completely transistorized, draws only 54 milliwatts of power, does not require a temperature controlled oven, and does not interact with similar oscillators located nearby.

26. Various means of further improvement in performance are readily apparent if desired. Much greater long-term stability

could be incorporated by the use of a temperature controlled oven for the tuned circuit elements but at the cost of much higher power consumption. Different arrangements of varicaps could be used to change the available magnitude of frequency control. Another method of improving the frequency stability would be the addition of a mu metal shield around the coil. It has been determined experimentally that bringing a moderate size permanent magnet up close to the copper shield can will produce temporary frequency changes of the order of 1 cps without the use of such a magnetic shield.

27. The oscillator as it stands is competitive in frequency stability with non-temperature controlled crystal oscillators. Unlike crystal type oscillators its frequency can be easily changed over appreciable ranges by an input control voltage.

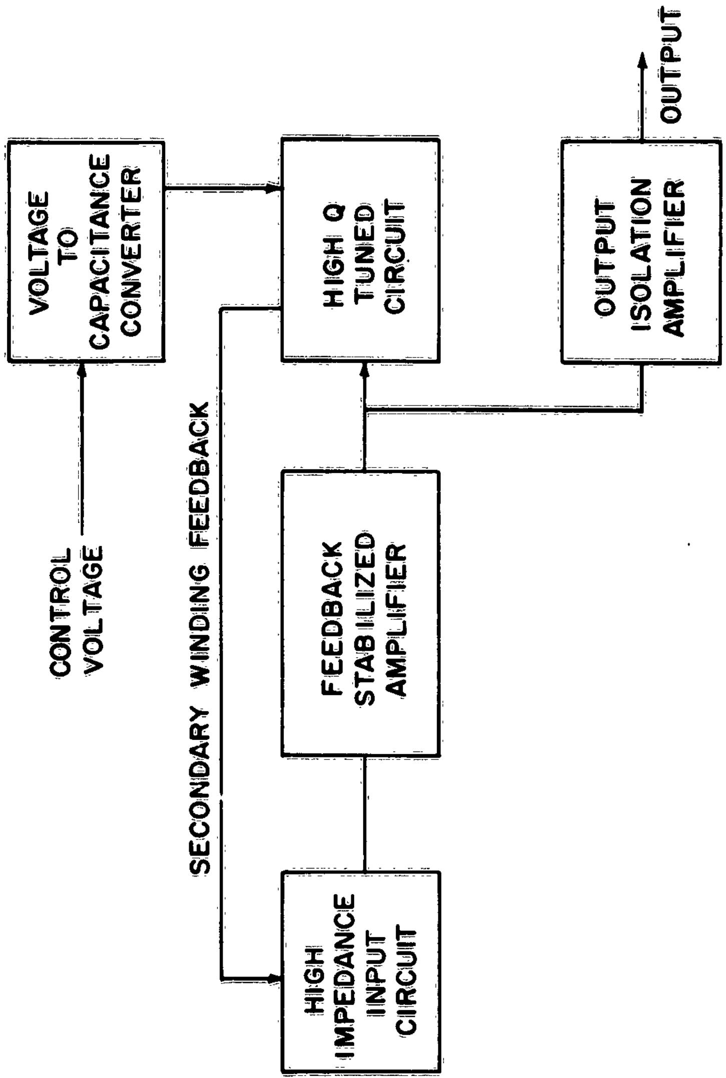

FIG. 1 BLOCK DIAGRAM OF THE OSCILLATOR

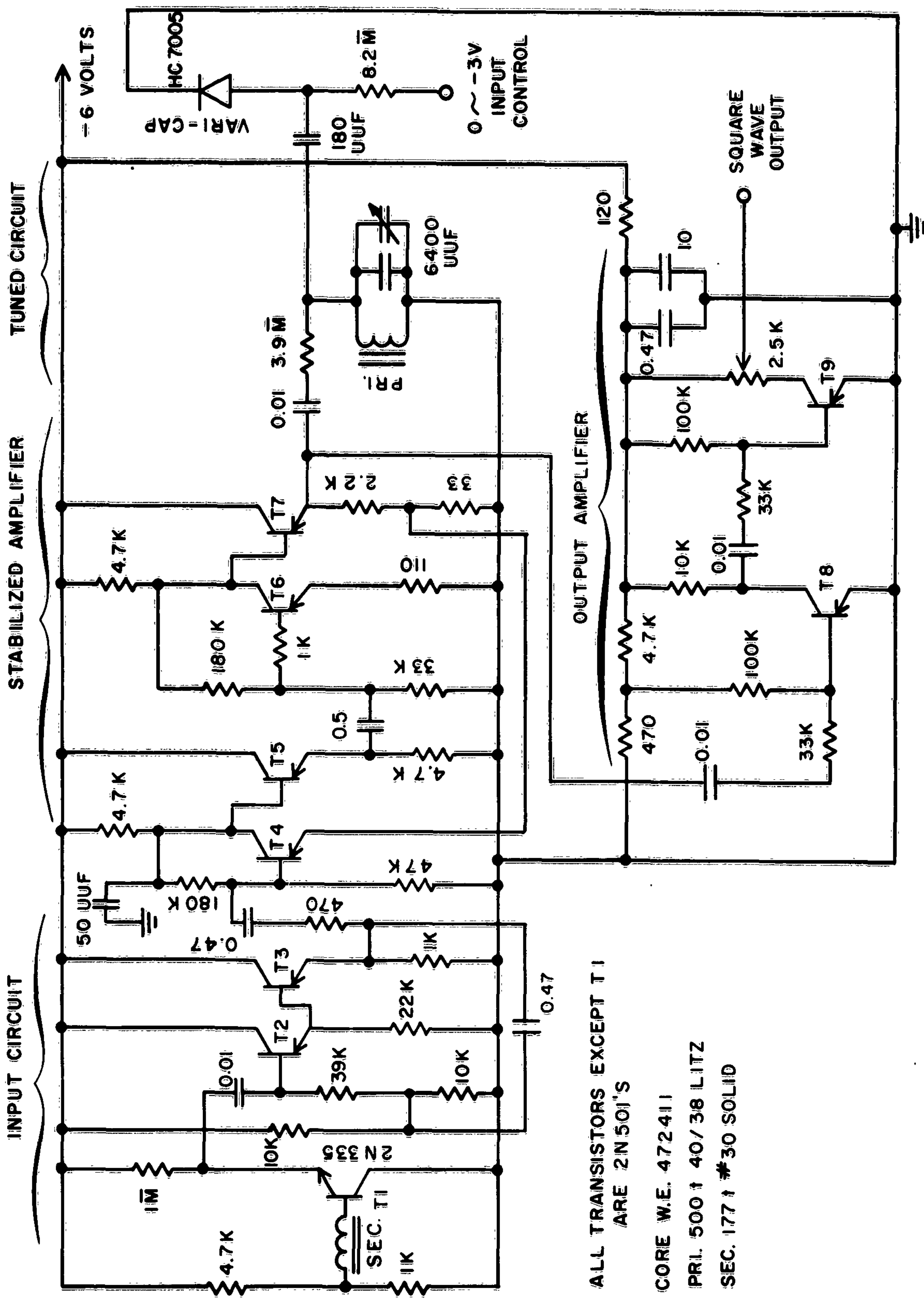

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FIG. 2 OSCILLATOR CIRCUIT DIAGRAM

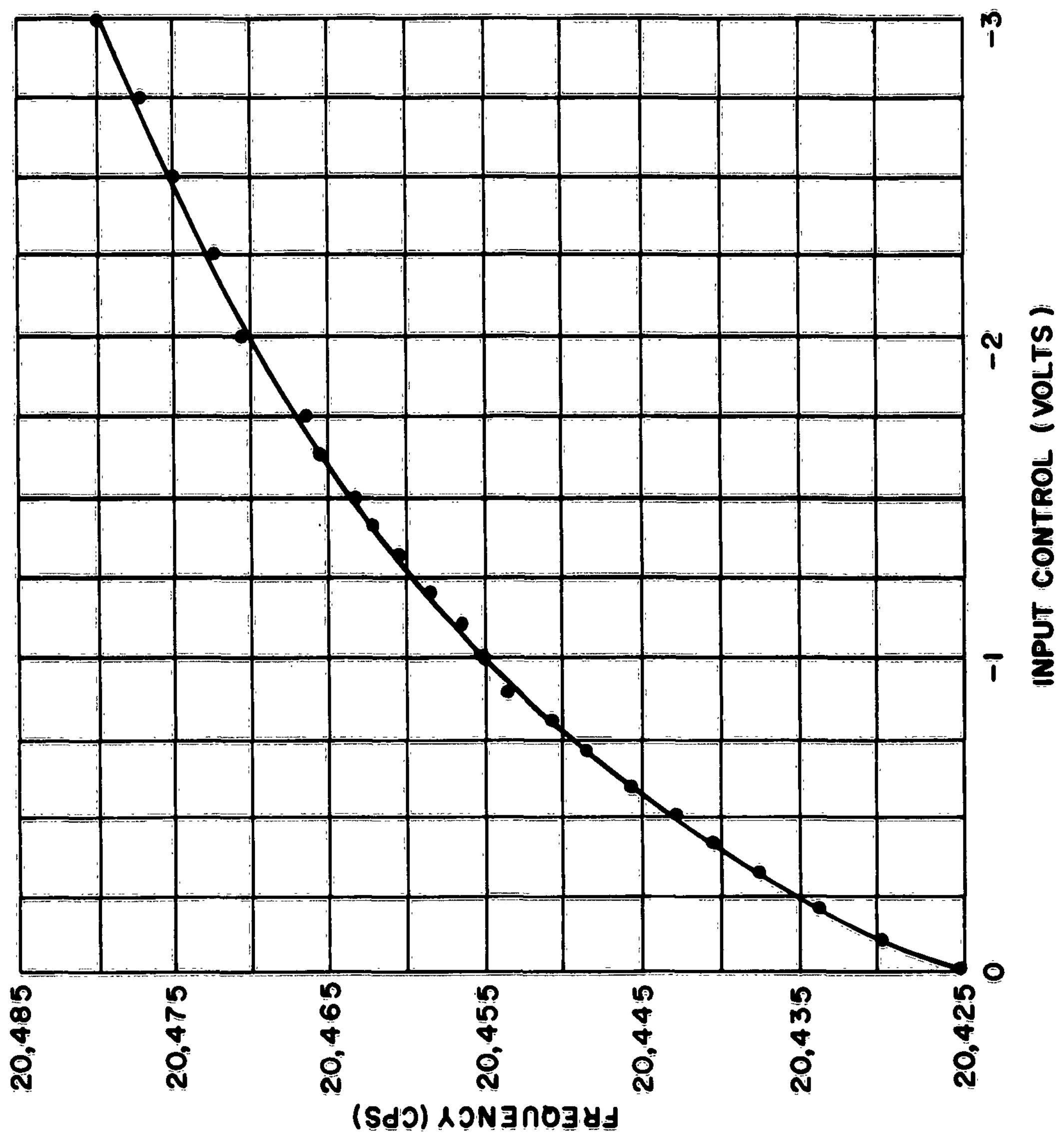

FIG. 3 FREQUENCY VS CONTROL VOLTAGE

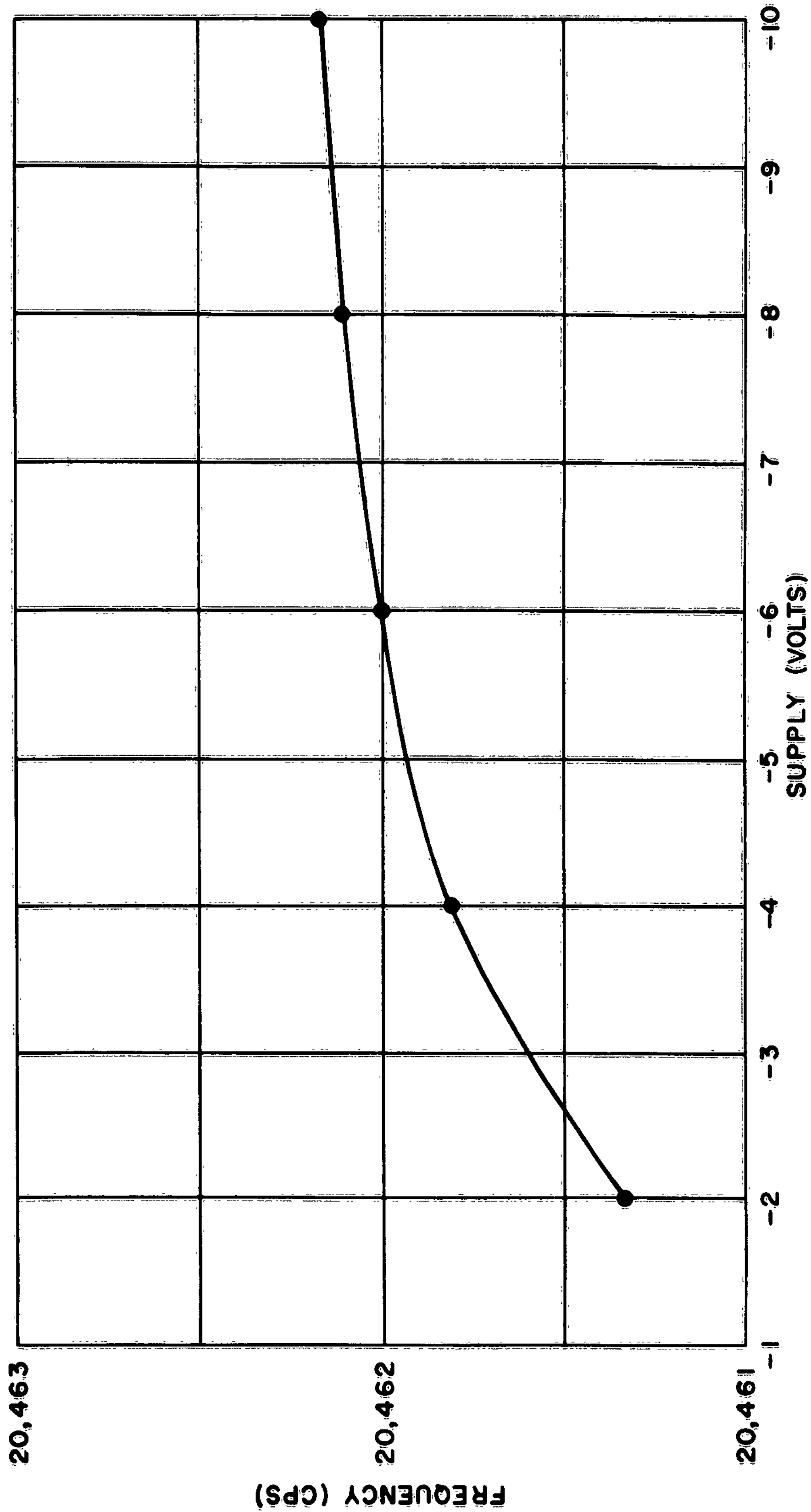

FIG. 4 FREQUENCY VS POWER SUPPLY VOLTAGE

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SOURCE	NOL technical report	NOLTR	SECURITY CLASSIFICATION AND CODE COUNT	Unclassified - 15	UØ15
REPORT NUMBER	62-105	62Ø1Ø5	CIRCULATION LIMITATION		
REPORT DATE	16 August 1962	Ø862	CIRCULATION LIMITATION OR BIBLIOGRAPHIC		
			BIBLIOGRAPHIC (SUPPL., VOL., ETC.)		

SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Oscillators	OSCL	Power supplies	POWS		
Transistorized	TRNT	Temperatures	TEMP		
Frequency	FREQ	Measurements	MEAU		
Stability	STBI				
Voltage	VOLT				
Controlled	CONT				
Variable	VART				
Oscillators (Design)	OSCLD				
Oscillators (Tests)	OSCLT				
Oscillators (Operation)	OSCLI				
Circuits	CIRC				
Amplifiers	AMPL				

PRNC-NOL-5070/28 (5-62)

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 62-105)
A STABLE VOLTAGE-CONTROLLED VARIABLE FREQUENCY OSCILLATOR (U), by Charles B. Leslie. 16 August 1962. 14p. charts, diagrs. Task NOL 396.

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Abstract card is unclassified

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2. Oscillators - Stability
3. Oscillators, Transistorized
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III. Project

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A STABLE VOLTAGE-CONTROLLED VARIABLE FREQUENCY OSCILLATOR (U), by Charles B. Leslie. 16 August 1962. 14p. charts, diagrs. Task NOL 396.

UNCLASSIFIED

A transistorized oscillator was required with a frequency stability of 1 part in 2×10^5 per hour. The frequency was 20.460 kc, variable $\pm$ 15 cps by a dc control voltage. The design philosophy and techniques are presented, including a high Q tuned circuit, frequency variation control, feedback stabilization, temperature compensation, and thermal filtering. Test results show that all requirements were met or exceeded. Methods of measuring the frequency to this accuracy are discussed.

Abstract card is unclassified

1. Oscillators, Frequency
2. Oscillators - Stability
3. Oscillators, Transistorized

I. Title
II. Leslie, Charles B.
III. Project

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